High Frequency Acoustics and Signal Processing for Weapons

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LONG-TERM GOALS

Task 1: The long-term goal of this task is to determine, for a broad range of frequencies (nominally 10-100 kHz), the limitations imposed by the oceanic environment on the exploitation of coherent signal structure. This understanding is required in order to optimize sonar signal processing structures (e.g. channel conditioning, especially in shallow water), for wideband signal and processor design, and for acoustic propagation modeling.

Task 2: The long-term goal of this task is to develop the capability to predict the dynamic and spatial characteristics, and the corresponding acoustic response (attenuation, local sound speed, and backscattering strength), of the bubbly wakes of Navy warships. We seek a predictive capability for how acoustic propagation and scattering vary with frequency, source-receiver geometry relative to the wake, and the shape and speed of the vessel, as well as the spatial and temporal statistics of attenuation and scattering strength in the wake.

OBJECTIVES

Task 1: Since coherent signal processing relies on the signal remaining so, while the interference does not, the experimental and theoretical objectives focus on signal coherence as a function of (elapsed) time and frequency (separation and/or bandwidth), and in particular, impact of the medium and the development of a predictive capability. The scientific objectives of this task are to:
1. Directly measure the time and frequency coherence of individual paths in an acoustic ocean channel while varying the signal bandwidth and center frequency, as well as the source-receiver geometry, and characterizing the ocean boundaries and volume
2. Investigate the physical mechanisms which impact propagation through the ocean channel and which limit acoustic coherence
3. Develop acoustic propagation models which predict acoustic coherence
4. In the far term, investigate signal processing architectures that exploit knowledge of oceanic time and frequency behavior.

Task 2: The scientific objectives are to understand and develop satisfactory models for (1) the spatial and temporal variation and size distribution of bubbles found in ship wakes and (2) acoustic propagation through, and scattering from, the complex in-water media caused by a warship wake.

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14. ABSTRACT

The long-term goal of this task is to determine, for a broad range of frequencies (nominally 10-100 kHz), the limitations imposed by the oceanic environment on the exploitation of coherent signal structure. This understanding is required in order to optimize sonar signal processing structures (e.g. channel conditioning, especially in shallow water), for wideband signal and processor design, and for acoustic propagation modeling

15. SUBJECT TERMS

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APPROACH

Task 1: Our approach to directly measuring temporal and frequency coherence utilizes both single pure tone (PT) and FM sweep signals. Concurrent environmental sampling is accomplished using these instruments:

- ASD Sensortechnik towed CTD string
- Reson 8101 multibeam sonar
- RDI 300kHz ADCP
- AXYS directional wave rider buoy

The received signals are groups of arrivals, each consisting of a direct path, a surface bounce path, and often one or more fully-refracted paths, with each group separated by 128ms, the transmission repetition rate. Variation between different arrivals or paths, provides a means of estimating temporal coherence. Frequency coherence is obtained from variation in the correlation between the transmitted and received signal with center frequency and bandwidth.

It is important to note that we are investigating 10's of kHz center frequencies and bandwidths up to 22kHz, both of which are significantly greater than those used by most other researchers. There are few published measurements of temporal or frequency coherence for high frequencies [1-5]. We find that signal coherence remains high (>50%) for larger bandwidths and longer times than intuition had led us to expect [6].

Task 2: Our approach has been to:

(1) Improve the wake hydrodynamic/bubble field description.

(2) Develop a fast, in-house capability to evaluate effects of the wake bubble field on acoustic propagation.

(3) Improve acoustic propagation modeling for inhomogeneous media.

(4) Investigate of how the spatial distribution of bubbles affects variability in acoustic response.

To better describe the wake field, we have developed a full-two-fluid bubbly flow model based on modern multiphase Computational Fluid Dynamics (CFD) technology. In the early years of this project, we focused on the complex transport and generation of bubbles in and near the propulsor. The dominant effect of bubbly propulsor flow physics was identified as a critical and missing element of the ONR 6.1 Free Surface Turbulence and Bubbly Flows program directed by Dr. L. Patrick Purtell, at his 2003 program review at CalTech [7].

More recently, we have focused in two objectives:

1) Development of a hybrid Reynolds Averaged Navier Stokes (RANS)/Destached Eddy Simulation (DES) technique for solving the instantaneous hydrodynamic and bubble field in the ship wake, and

2) Development of a complete engineering-level model for the hydrodynamic wake.

<u>Wake hydrodynamic modeling using DES</u>: The turbulent wake left by a ship can be qualitatively viewed as a large population of different size eddies. The RANS solutions represent an average of the flow and hence all of these stochastic motions are smoothed out. This implies that the level of detail required to capture more completely the turbulent transport of the bubble field is non-existent in RANS solutions. Due to the large Reynolds number of the flow in ship wakes, $\sim O(10^7)$, numerical solutions aimed at resolving all of the scales, or most of the energy containing motions are prohibitively expensive to implement. The alternative is DES [8], which is a hybrid implementation of large eddy scale (LES) and RANS. It allows for resolution of most the energy containing eddies in the wake region, or the region of interest, and RANS type of treatment everywhere else, so that the costs associated with high resolution are only confined to the region of interest.

Engineering-level wake model: The goal of the this effort has been to establish a complete in-house modeling toolkit, where the analyst inputs geometry and operating conditions (speed, orientation, sea-state), runs RANS analyses of the ship, near wake and far wake, processes the wake to accommodate (model) instantaneous turbulence effects, and performs PE acoustic analysis on the wake. This procedure is shown in Figure 1.

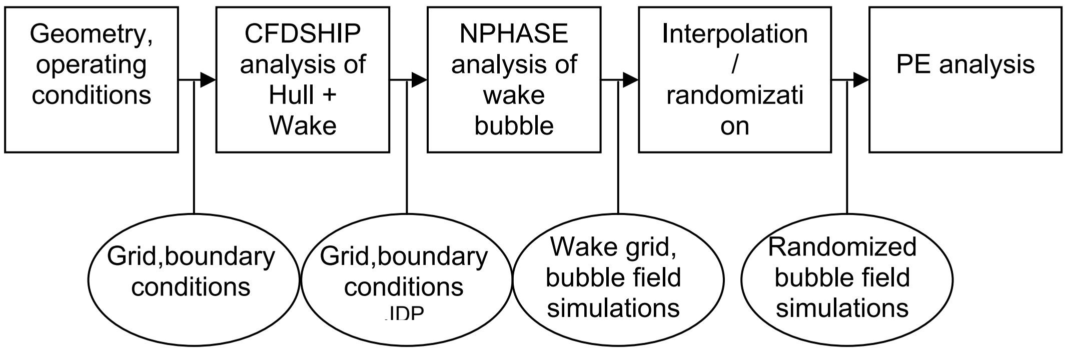

Figure 1: Flow chart for complete engineering-level bubbly hydrodynamics model.

Acoustic propagation modeling. To model acoustic propagation through the wake, have focused on a parabolic approximation to the wave equation (PE) because of its capability to deal with range and depth-dependent media. Under this project, during past years, an existing two-dimensional PE model [9] was adapted for use in the ship wake [10], applied to a simple, unclassified 3D random wake acoustic field developed from open literature sources [11], and transitioned to the Navy (ONR and NAVSEA) surface ship torpedo defense (SSTD) programs, where it is currently used extensively. Our current effort is to directly connect the wake hydrodynamic and bubble transport model to the acoustic modeling code. Also, working closely with the Navy's SSTD program, the capability of the PE code has been expanded to provide time domain, pulse propagation visualization and ported to an FFT card for faster execution speed.

Effects of wake spatial variability. Using PE to model acoustic propagation through the wake uses an effective medium approach, in which the two-phase bubble-water field is replaced with a single-phase medium that is dispersive and exhibits frequency dependent attenuation and scattering. The statistics describing propagation through bubbles, which can be derived using multiple scattering theory, as well as the inherent assumptions contained in the theory, are being examined in both a theoretical sense and in a laboratory environment. In particular, potential deviations from the classic approach to multiple scattering theory caused by 'patchy' bubble clouds are being investigated.

WORK COMPLETED

Task 1: During 14-18 August 2002, acoustic measurements were made twice daily using 20kHz and 40kHz center frequencies, 0.14ms and 1ms PT signals, and 8ms FM signals with 1, 7, 13 and 22kHz bandwidths. The geometry is shown in Figure 2. Environmental conditions were relatively calm, with wind speed averaging 7kts and rms wave height below 0.1m (the latter due to screening by nearby San Clemente Island). Measurements from the fifteen sensor CTD chain allowed for very fine resolution of horizontal structure in the sound speed field (Figure 2). In the upper 20m, Langmuir circulation apparently has pulled warmer, surface water down to depths where the surrounding temperature and sound speed are much lower. Sound speed anomalies at 20m to 50m depth are likely caused by

internal waves. The acoustic paths shown in Figure 3 make it clear that different paths will be subjected to different types and levels of medium variability.

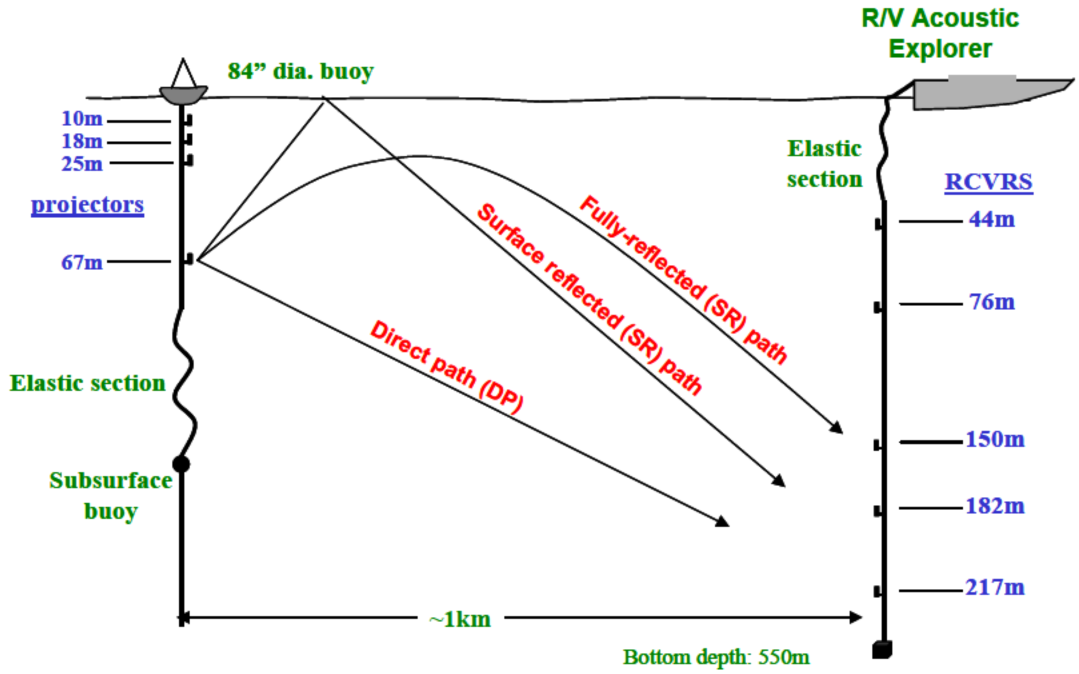

Figure 2: August 2002 measurement geometry. The receive array was suspended from R/V Acoustic Explorer, which was in a three-point moor, using an elastic member. Acoustic projectors were mounted on the riser of an elastically moored surface buoy and controlled via RF link R/V Acoustic Explorer.

The current profile displayed in Figure 4 shows daily periodic variation. For visual simplicity, data points for which current speed is less than 0.1 m/s are blacked out. Times of high current activity coincide with daily transition from high tide to low tide. Four of the seven acoustic data sets were analyzed and compared to the current activity. One of those four sets, one occurred during a time of high current and three occurred during times of relative quiescence. During the active time (the data in red in Figure 3), the mean current speed between 15 m and 40 m depth was approximately 0.25 m/s. During the quiescent times, the mean current speed at these depths was .05 and 0.6 m/s, and during the time of intermediate activity, the mean speed was .10 m/s.

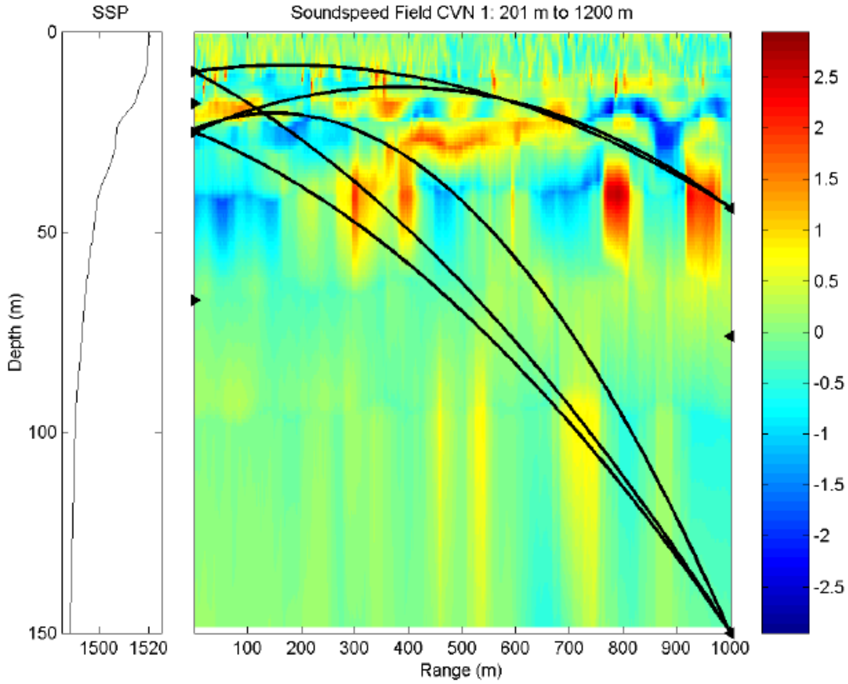

Figure 3: August 2002 measurements of mean sound speed (left) and sound speed anomaly (right) with selected rays superimposed

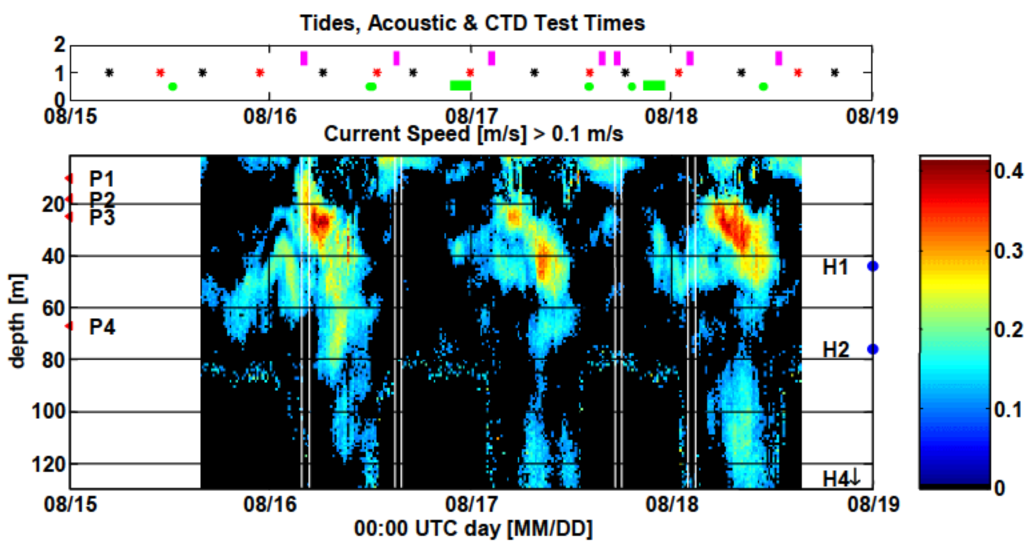

Figure 4: Current measurements made during the August 2002 at the experiment site.

Task 2:
Wake hydrodynamic modeling using DES: The work completed under this sub-task includes implementation of DES in CFDSHIP [12], validation efforts for canonical separating bluff body flows representative of the surface ship near wake region, and application to the Model 5415 hull form. Several of these results have now been published [13] and selected results are presented below.

Engineering-level wake model: CFDSHIP code is employed in the model to compute the single-phase RANS flow field about the ship and wake (pressure and velocity boundary conditions, including the effect of propulsors on the wake flow). Then, using the CFDSHIP solution, the multi-phase NPHASE code, used in the earlier propulsor flow effort, is used to evolve a Reynolds Averaged bubble distribution through the wake for a range of bubble sizes and arbitrary initial data plane (IDP) bubble number density distribution. These solutions fully accommodate bubble size, number density and IDP physics, but in an ensemble averaged fashion. The next step involves appropriate interpolation and randomization of the predicted bubble distributions using the technique of Rapids and Culver [11]. The randomized "instantaneous" bubble distribution is then input to the PE analysis. The work completed in this effort involves the software interfacing of the various elements of the model, and numerous analyses of the 5415 configuration.

Acoustic propagation modeling. A time domain version of PE was developed, which enabled visualization of pulse propagation through the bubbly wake field [14]. The frequency-dependent attenuation and refraction caused by particular size distribution of bubbles were clearly visible and provided an understanding of WWII-era ship wake acoustic measurements. Also, progress was made linking the wake hydro model and the PE propagation model [14]. The difficult aspect here is interpolating the vector-based output of the hydrodynamic code onto a rectilinear grid required by PE.

Effects of wake spatial variability. A predictive capability describing the variance in acoustic observations due to multiple scattering by bubbles has been developed, including a more accurate derivation for variance then was previously available (i.e. includes more orders of multiple scattering). This capability has been verified in laboratory generated bubble clouds [15]. In order to examine the effect of 'patchy' bubble clouds, a non-acoustic imaging technique to measure the spatial structure of the bubbles based on laser tomography is currently being developed

RESULTS

Task 1: One result obtained thus far is that the correlation of the surface reflected acoustic path was found to decrease with increasing signal bandwidth (Figure 5) [6, 16]. In this still preliminary look, the fall off in correlation appears to be consistent with theory due to Dahl relating increasing time spread to decreased frequency coherence [5].

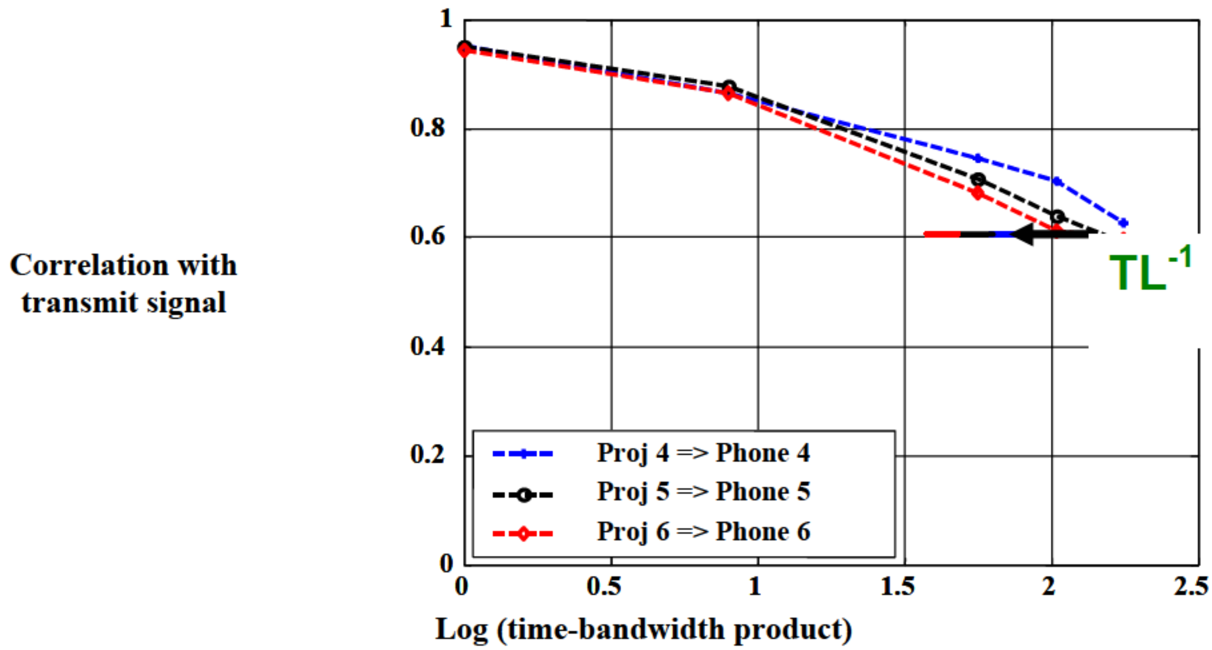

Figure 5: Measured correlation of the surface reflected path with the transmitted signal as a function of increasing signal bandwidth (dashed lines) along with theoretical prediction from Dahl [ref] (T is signal duration, L is a measure of time spread).

We have made progress but as of yet do not have a definitive result comparing the scintillation index of direct path acoustic signals with measured spatial variability in the index of refraction, the latter obtained from towed CTD data. We find that the intensity of the received signal varies over a 30 sec window in a manner that changes over the 5 days on site (Figure 6). Some intensity variations persist over several seconds. Theory exists relating the scintillation index to the size and strength of inhomogeneities in the sound speed field [17]. Our current effort is to relate the theory to our measurements.

A third result, which limited space leads us explain in words rather than with a picture, relates the mean intensity of the received signal to the intermittent current observed in Figure 4. We find that, for projector-hydrophone paths that transect the current jet, the received intensity and scintillation index are higher when the jet is present. This is apparently due to increased scattering of sound into what would conventionally be referred to as a shadow zone [18-19].

Task 2:

<u>*Wake hydrodynamic modeling using DES*</u>*:* A recent example of DES output is shown below in Figure 7, where the CFDSHIP code evolved in the current program has been employed to model a flow separating at the trailing edge of a flat strut. The pictures clearly show the presence of a multitude of turbulent structures having a wide range of scales and in particular the presence of “rib” and “roller” instability modes.

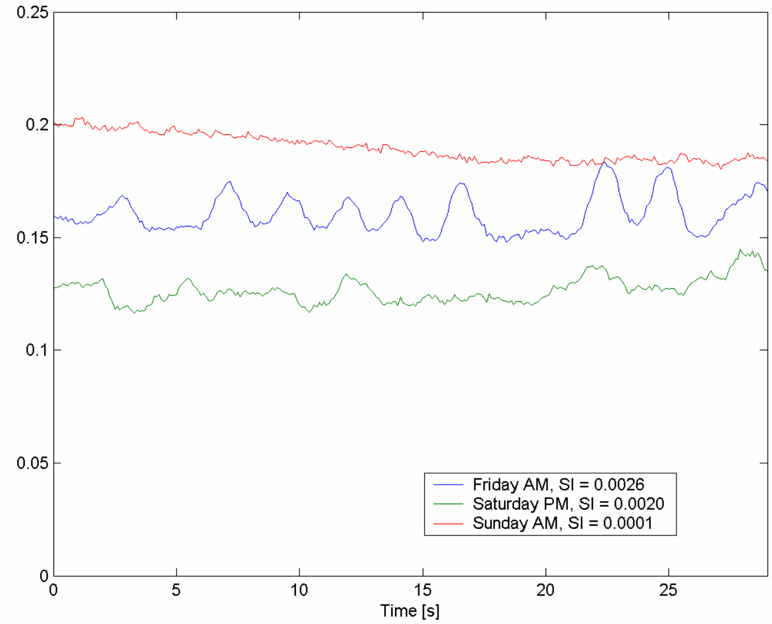

Figure 6. Intensity of the signal transmitted from the projector @ 25m depth and received by the hydrophone @ 150m depth at three measurement times. SI = scintillation index; signal transmission rate: 10/sec; Friday=16 Aug. 2002

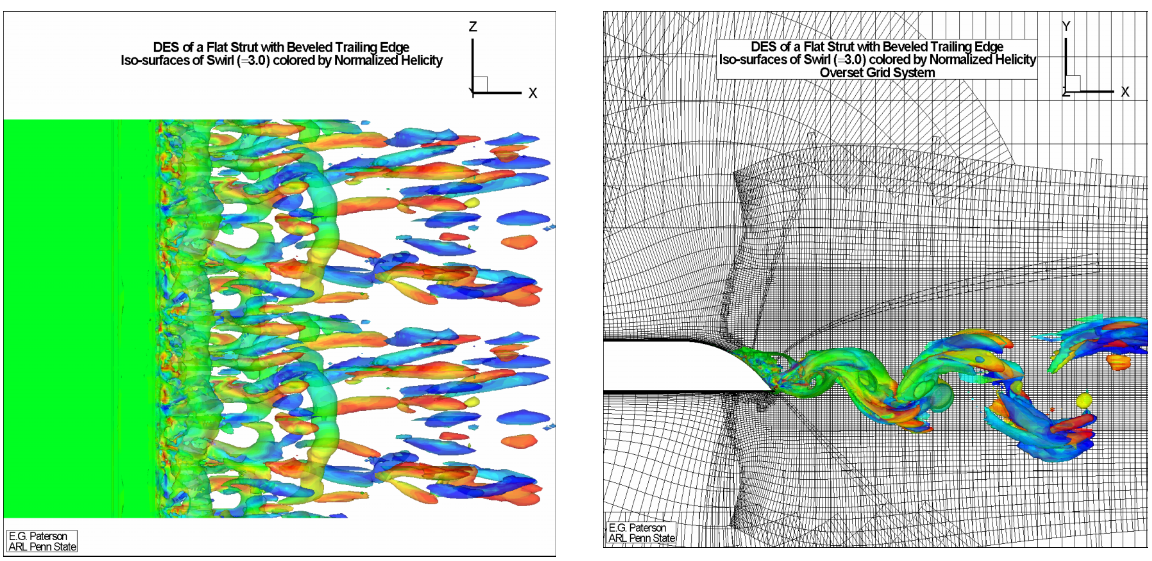

Figure 7: Flow separation in the trailing edge region of 2D strut captured using DES.

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<u>Engineering-level wake model</u>: Using the interpolation procedure developed under this program, the CFDSHIP results were used to initialize numerous NPHASE computations. For these analyses, a semi-cylinder domain was employed (see Figure 8), that extended from 0.05 to 10.00 ship lengths astern. An initial bubble distribution at the stern was constructed based on a model due to Hyman et. al [20], that accounts for bubble sources due to the hull-free-surface flow and ocean environment. An analogous

model was developed here to account for propulsor sources. Figure 8 shows elements of the predicted bubble field for a 200 μm distribution. Clearly evident in these simulations is the strong influence of the propulsor induced swirl on the bubble transport well down stream. The influence of gravity is also observed as many bubbles have been transported up and out of the free surface by x/L = 6. To date we have run numerous bubble diameters and are experimenting with IDP source distribution modeling. The next step in the process is to convert the NPHASE volume fraction predictions to bubble number density and to interpolate these distributions to a Cartesian grid. This interpolation process is carried out in the NPHASE postprocessor.

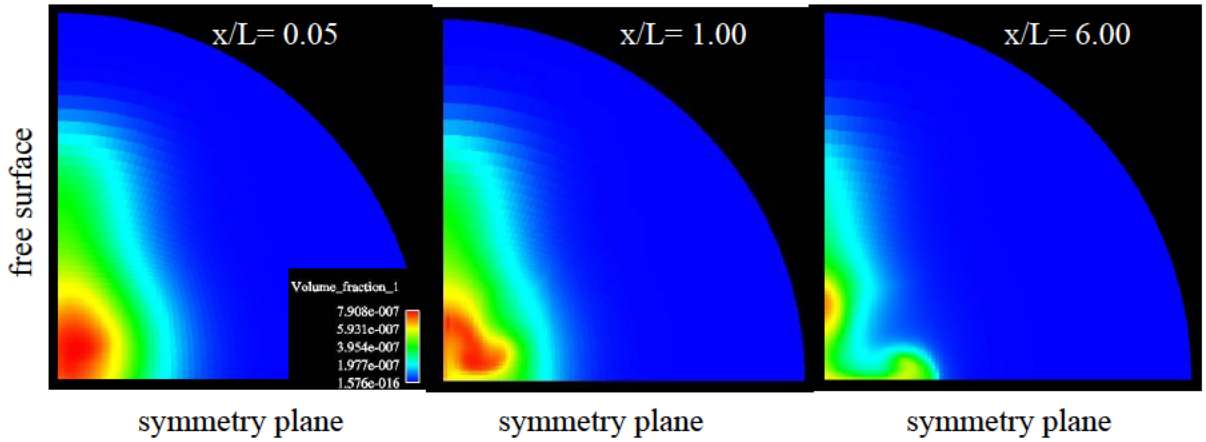

Figure 8: Elements of the NPHASE predicted bubble field distribution for a 200 μm distribution, propelled case. Shown are bubble volume fraction contours at 0.05, 1.00 and 10.00 ship lengths astern.

<u>*Acoustic propagation modeling*</u>. As an example of time domain PE output, Figure 9 illustrates the frequency dependence of propagation through the same bubble mass. The pulse is propagating from left to right, and it is clear that behind the bubble mass, the pulse is significantly attenuated at 30kHz but not at 10kHz. This is because the sound speed inside the bubble mass is lower than ambient at 10kHz, causing upward refraction, while at 30kHz, the sound speed inside the bubble mass is higher than ambient, leading to downward refraction and a shadow zone behind the mass. The dispersive nature of bubble distributions was shown, for example, by Commander and Prosperetti [21].

<u>*Effects of wake spatial variability*</u>. Figure 10 shows predicted and measured acoustic amplitude standard deviation of 5% of the mean value for a small source-receiver separation (<1m) and for small void fractions, O(1e-7). For larger source-receiver separation and/or void fractions, the standard deviation grows exponentially.

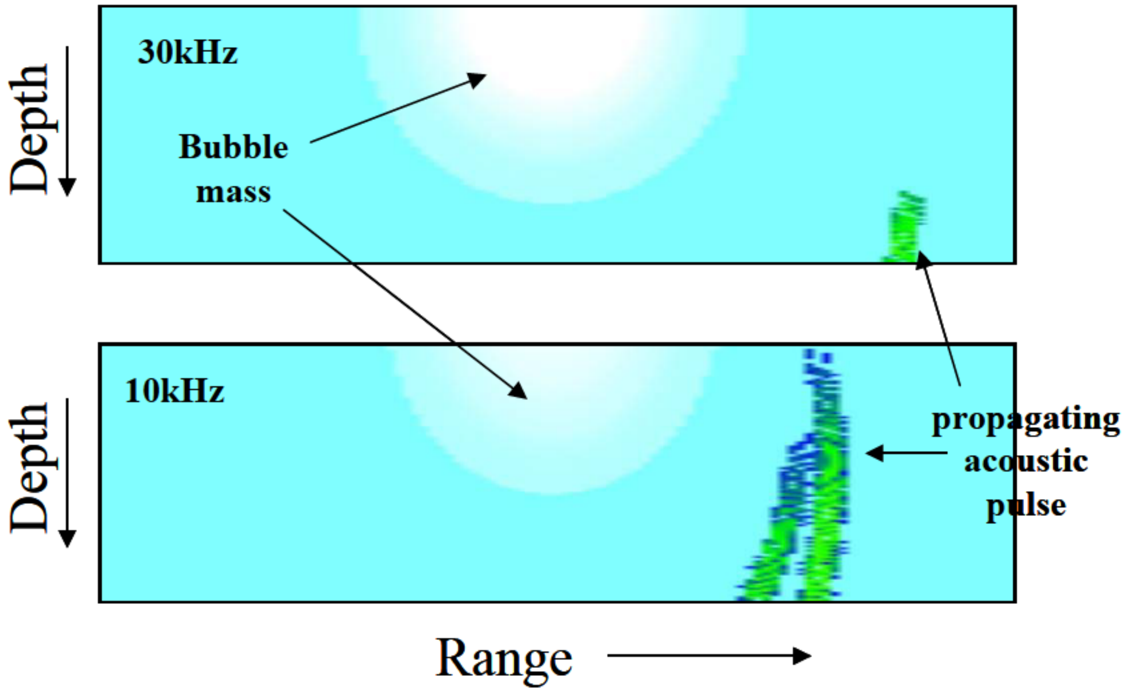

Figure 9: Frequency dependence of acoustic attenuation by the same bubble mass. The bubbles refract 10kHz sound upward and 30kHz sound downward.

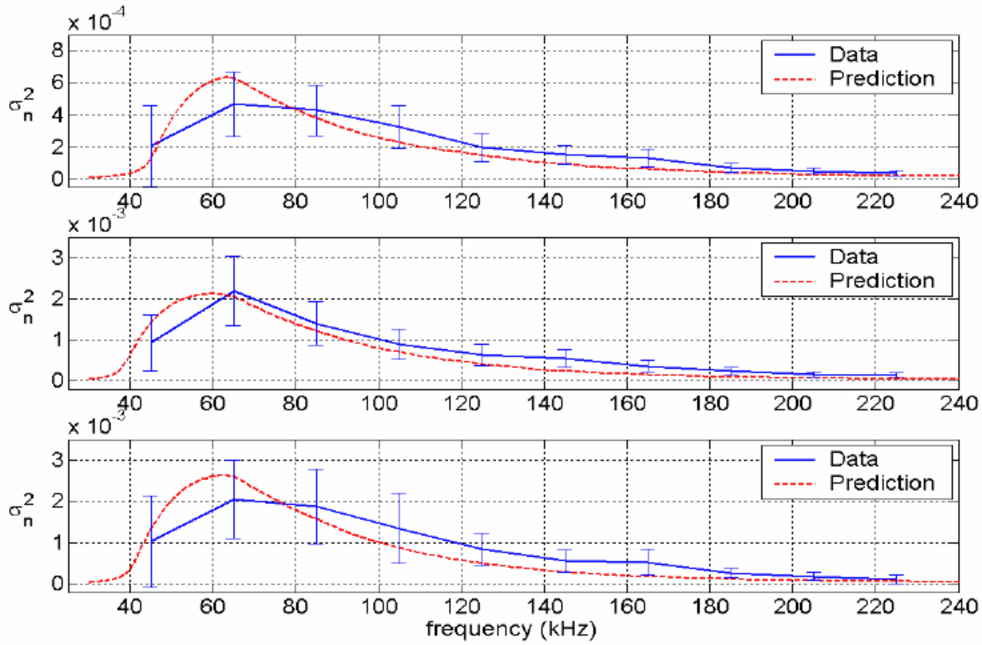

Figure 10: Comparison between predicted and measured normalized variance for three different bubble distributions in a laboratory environment. The error bars describe a 95% confidence interval.

IMPACT/APPLICATIONS

Task 1: The motivation for investigating acoustic coherence in the ocean channel is a desire to improve the performance of undersea weapon systems that utilize acoustics to detect, classify and localize the target. Our emphasis is on temporal coherence and broadband signals because the undersea weapons development community is increasing signal time-bandwidth product at traditional weapons frequencies. Advanced, coherent signal processing architectures are contemplated, whose effectiveness will depend upon the impact of the ocean environment on temporal and frequency coherence.

Task 2: Acoustic propagation in any homogenous bubble field becomes dominated by incoherent effects at even moderate ranges, and is thus highly variable. Understanding this variability, for both homogenous and inhomogenous (i.e. patchy) bubble fields is critical to evaluating sonar performance in ship wakes and other bubbly environments.
In general, understanding and being able to predict acoustic propagation through ship wakes is critical to the US Navy's development of an anti-torpedo torpedo (ATT) that can counter wake homing torpedoes. Since it is neither feasible nor affordable to conduct at-sea measurements using every ship class in every environment and using all possible combinations of ATT and threat geometries, a predictive model is required. Also, acoustic propagation through entrained air in water due to wind-wave action is important to the development of mine countermeasure systems for use in near-shore areas.

TRANSTIONS

The PE model adapted for acoustic propagation through the wake under Task 2 has been transitioned to the Surface Ship Torpedo Defense (SSTD) projects at ONR Code 33 and NAVSEA PMS 415. The model is currently interfaced to the Torpedo Requirements Model (TRM), which runs engagement simulations for performance prediction.

RELATED PROJECTS

Task 1: Closely related projects include: Peter Dahl (APL-UW) *High-Frequency Scattering from the Sea Surface and Multiple Scattering from Bubbles*; David Farmer (URI) *Turbulence, bubble distributions and high frequency propagation*, and Bill Hodgkiss and Bill Kuperman (MPL/SIO) *Fluctuations in High Frequency Acoustic Propagation.*

The Multi-Platform Broadband Processing Advanced Technology Demonstration (ATD) (Program Officer: Mr. Les Jacobi, ONR Code 333) has a goal of developing and demonstrating broadband processing across the mid- to high frequency band (weapon, submarine and surface ship platforms). Areas of focus in the ATD are broadband processing using multi-component simultaneous signals and coherent broadband processing. Measurements and modeling of frequency and temporal coherence produced by our work may be of direct relevance to this ATD. The Common Broadband Sonar System (CBASS) is also exploring applications of this technology.

Task 2:

- ONR 6.2 Counterweapon development program (Program Officer: T. McMullen)
- Tripwire Torpedo Defense System (PMS415, Program Officer: T. Goodall)

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HONORS/AWARDS/PRIZES
None.